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The Ribbon Laser

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Abstract
A new scalable fiber laser approach is described and modeled, based on phase- locking multiple gain cores in an antiguided structure. In essence, the waveguide is comprised of a periodic sequence of gain- loaded and no- gain segments having uniform refractive index(referred to as the "ribbon") encapsulated within a reduced index cladding region. Our calculations reveal that the constant index profile within the ribbon structure provides optimal mode discrimination; the refractive index must be constant within ~±0.001 to ensure single- mode operation for a 5-core design.. Periodic variation in refractive index and gain of the ribbon laser lead to the emergence of a photonic bandgap, in analogy to so-called "holey fibers". Our constant index design, together with the periodic gain profile, may be described as a photonic metal.

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We describe a new, robustly scalable technique for phase locking multiple gain cores in a fiber structure based on anti- guiding or radiative coupling[1].In our ribbon structure, an outer low index cladding surrounds an inner region in which multiple gain cores alternate with non-gain cores in a periodic array.

The ribbon structure described in this paper uses a non-evanescent approach to coherently phase together the gain- loaded cores. In this approach, the gain elements are radiatively coupled in a "leaky" waveguide array, analogous to the most successful scheme for phasing laser diode elements[1,2]. A lineout of a typical refractive index profile is shown in Fig.1.

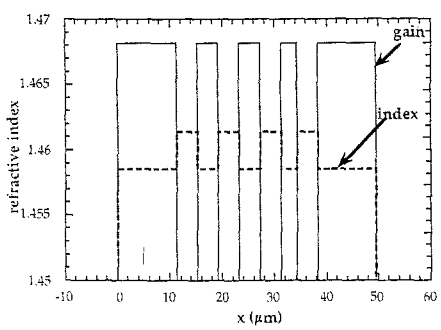

Fig. 1: Typical one dimensional refractive index and gain profiles as function of transverse coordinate. Gain coincides with lower index segments.

We used a 1D eigenmode analysis method to satisfy a design criterion that the electric field should null at the center of the no-gain regions of the waveguide, accounting for the fact that the boundary conditions at the edge of the structure are different from those in the interior. In this structure, the pump-cladding index region has refractive index 1.45, the gain-loaded portion of the waveguide has refractive index 1.4585, and the no-gain regions of the waveguide have refractive index 1.4614. We arbitrarily took the vacuum wavelength of the waveguide radiation to be 1.05 μm and the widths of the interior gain and no- gain segments to be 4 μm. With these choices, the mode having one lobe associated with each gain region has a wavevector value of 8.725/μm and the gain-loaded segments at the ends of the waveguide region have widths of 11.23 μm making the total width of the waveguide region 50.45 μm. Fig. 2 gives a summary of this structure's eigenmode spectrum in a plot of mode overlap with gain regions vs effective index value. Note the jump in both effective index and gain overlap, i.e. real and imaginary parts of the modal propagation constant, indicates a photonic bandgap. Indeed the symmetry of the modes on either side of this jump are just what one expects at the Brillouin zone boundary of the periodic structure. The mode discrimination is good across this jump, but not as good with respect to other nearby anti-guided modes (to left of gap in fig.)

As an alternative to the periodically modulated index structures just considered, we next evaluated a waveguide structure having uniform refractive index across its aperture and only modulated the gain profile periodically. To keep a connection with the previously analyzed case displayed in Fig. 2, we keep the clad index value at 1.45, the waveguide region at a constant index of 1.4585, and the overall width of the waveguide at 50.45 μm. We applied the same design procedure as before. In this case, the mode having one lobe associated with each gain region has a wavevector value of 8.723/μm. Fig. 3 gives a summary of this structure's eigenmode spectrum in a plot of mode overlap with gain regions vs effective index value. In this case, the structure exhibits very good mode discrimination since it is only the gain which determines the optimal spatial frequency.

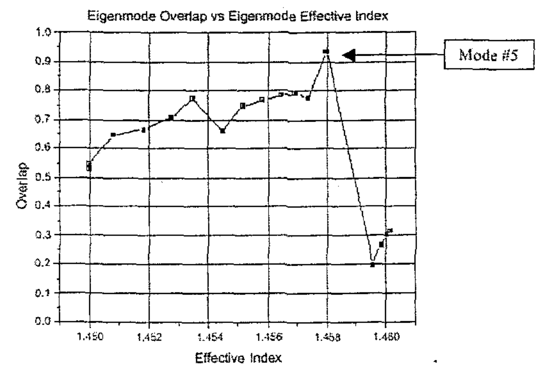

Fig. 2: The eigenmode overlap with the gain region is plotted against effective index for the structure with interior indices of 1.4585 and 1.4614. Mode #5 (counting from the right) was designed to have a single intensity lobe for each of the gain-loaded segments in the waveguide region.

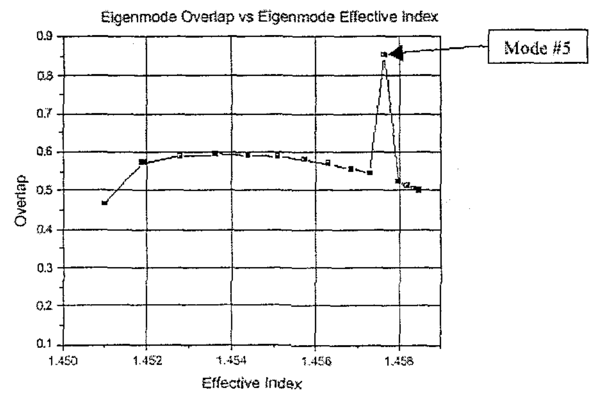

Fig. 3: The eigenmode overlap with the gain region is plotted against effective index for structure with constant interior index of 1.4585..

We carried out detailed beam propagation[3] simulations for a three dimensional structure with rectangular cores as shown in Fig. 4. The lower part of this figure shows the mode shape selected by the gain distribution. The farfield pattern for this mode is multi-lobed (Fig. 5a) since the mode is nearly pure sinusoidal, but this pattern can be corrected with a phase plate as shown in Fig.(5b).

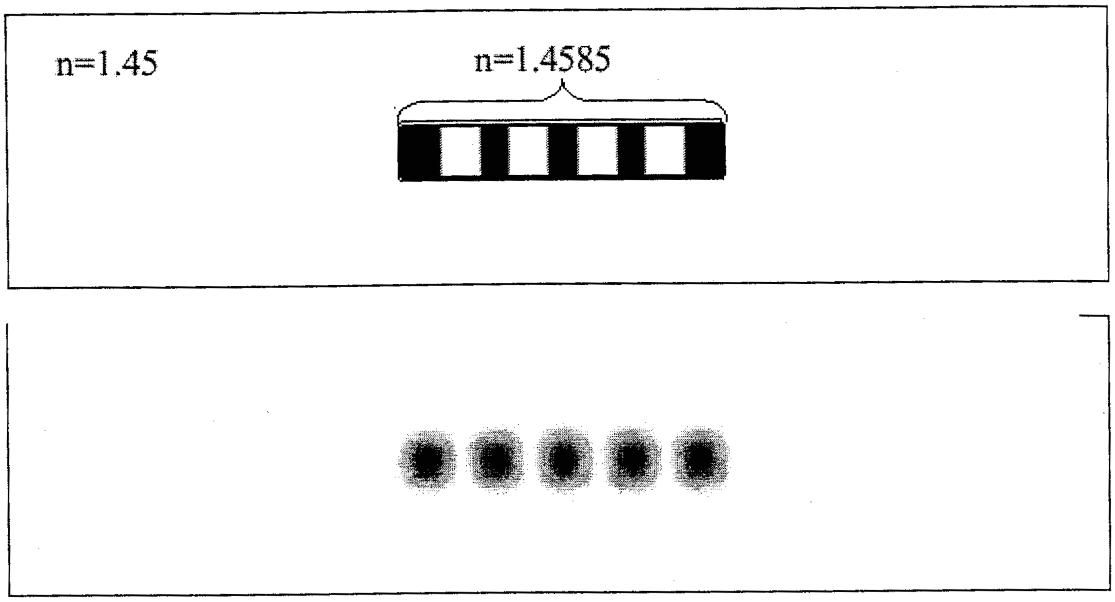

Fig. 4: Cross sectional view of ribbon structure with 2 transverse dimensions. The dark regions in the upper picture indicate the gain-loaded portions of the waveguide. The refractive index is constant throughout the waveguide region and equals 1.4585. The waveguide region is 6 μm high, the end pieces are 4.5 μm wide, and the central segments are 4 μm wide.

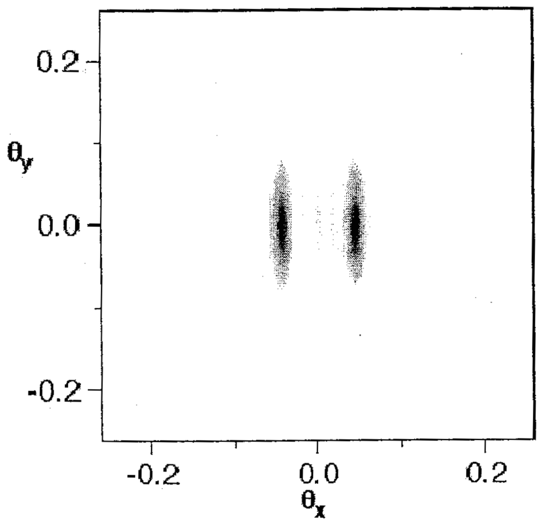

Figure 5(a): Uncorrected farfield of ribbon structure of Fig.(3). Farfield lines separated by 132 mrad.

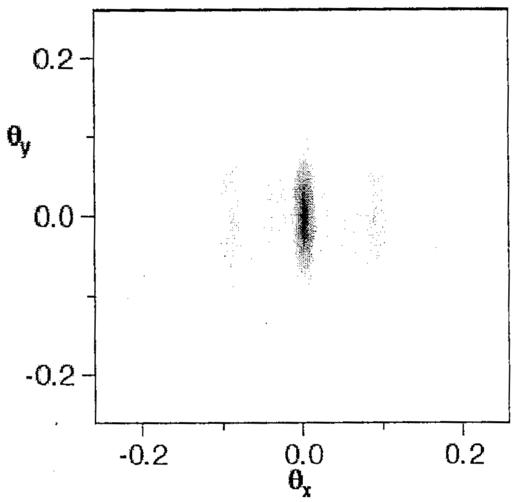

Figure 5(b) Farfield after correction with simple phase plate. Approximately 2/3 of the total energy is contained in the central peak

We also explored the sensitivity of the design to various possible fabrication errors. Fig. 6 shows the difference in gain between highest and next highest gain modes as a function of index error in the waveguide interior. The allowable error becomes less as the structure is scaled up in number of cores. From this and other studies, it appears reasonable to expect that 100 core structures will be feasible.

In conclusion, robust scalable ribbon structures of up to 100 gain cores should be feasible. We plan to fabricate a five core prototype to prove the principle.

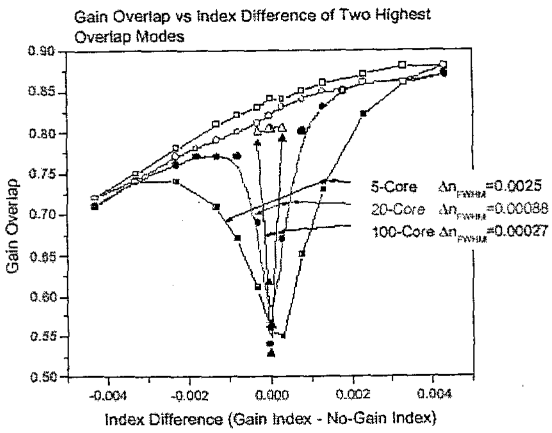

Fig. 6: Overlap vs. index difference for one-dimensional structures having a systematic index variation between the gain and no-gain regions. Three different structures are investigated here consisting of 5, 20, and 100 cores; respectively. For each structure investigated, the gain overlap of the highest overlap and next highest overlap mode are plotted against the systematic index variation.

References:

[1] D. Botez and D. R. Scifres, *Diode Laser Arrays*, (Cambridge Univ. Press 1994)

[2] D. Botez and A.P. Napartavich, "Phase-Locked Arrays of Antiguides: Analytical Theory," IEEE Journal of Quant. Elec. **30**, 975-980, (1994); D.Botez, A.P. Napartovich, C.A. Zmudzinski, "Phase-Locked Arrays of Antiguides: analytic Theory II," IEEE Journal of Quant. Elec. **31**, 244-253, (1995)

[3]. M.D. Feit and J.A. Fleck, Jr., "Computation of mode eigenfunctio ns in graded index optical fibers by the propagating beam method," Appl. Opt. **19**, 2240-2246, (1980); M.D. Feit and J.A. Fleck, Jr., "Mode properties of optical fibers with lossy components by the propagating beam theory", Appl. Opt. **20**, 848-56 (1981)

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